GEOPHYSICAL MODEL NLINC'J'1ONS FOR THE SEA STATE BIAS IN SATELLITE ALTIMETRY

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The sea state bias in altimeter measurements Of sea surface height have been investigated by many authors, resulting in several proposed algorithms of the form SSB = εH where H is the significant wave height (SWH) and ε is a nondimensional function of wind and wave parameters. All known algorithms are presently rated. The most popular, linear model of the form $\varepsilon = a_0 + a_1 U$ is shown to yield an improvement over the simplest algorithm with a constant ε. A three-parameter form $\varepsilon = a_0 + a_1 U + a_2 H$ produces even belle.r results. However, the accuracy of the polynomial mode.]s is below that obtained with a two-parameter, physically-bawd model relating ε to the pseudo-wave-age ξ: $\varepsilon = M \xi^{-m}$. The ξ is estimated using altimeter wind U and SWH: $\xi = A(gH/U^2)^v$ where A and v are constants. By analyzing the performance of different models we conclude that further progress can hardly be achieved by raising the degree of the polynomial for $\varepsilon(U,H)$. Physically-base.d approaches employing a small number of adjustable parameters and the.orc.tically justified non-dimensional combinations of external wind and wave factors appear to be more promising.

1. Introduction

The sea state bias (SSB) is the difference between the. apparent mean sea level - as "seen" by an altimeter - and the true mean sea level - defined as the mean height found by averaging the surface ele alien field over the footprint area. While a number of algorithms for the SSB correction have been propose.d in recent years, their actual pcrfcrrlnancc.under realistic ocean conditions has not been tested. More importantly, the.rc: iscol~sidcrablc dis:igrccll~cl~t in the literature as to the functional form in which SSB is to besought. Most of the contemporary models assume SSB to be linearly proportional to SWH. The proportionality coefficient, ε, (introduced by equation (1)) is (almost linearly) related 10 the local wind. An exception is given by a physically-based model [Glazman and Srokosz, 1991; Fu and Glazman, 1991] which indicates that, for global data, the SSB dependence on SWH is weaker: at a given wind, SSB is approximately proportional to the square root of SWH, although the wind speed dependence of the proportionality coefficient remains close to linear. The theory suggests that SSB is controlled primarily by the degree Of the sea development which can be crudely quantified by two non-dimensional parameters - the wave age and the ratio of the wind fetch to the intrinsic inner scale of the. gravity wave turbulence. Practical implementation of this model requires expressing these factors in terms of the sate.llilc-rcpor(c.d quantities - wind speed and SWH, which is not always possible. '1'bus, the. central issue addressed by the present work is the form in which the SSB correction should be sought and limitations of the prr.sent paradigm.

A detailed description of the experimental approach and the results of this work are provided in [Glazman et al., 1993].

2. Sea state bias and its geophysical model function

The SSB is usually sought in the form

$$\eta = \varepsilon H \tag{1}$$

where ε is a non-dimensional coefficient varying from 0.01 to 0.06- as follows from a large number of studies, and H is the significant wave height (usually denoted as $H_{1/3}$). This form has a theoretical basis [Jackson, 1979], [Glazman and Srokosz, 1991]. The theory also predicts that ε, which accounts for both the distortion of the return pulse shape and the delay in the pulse return, is a function of the wave age ξ and of the ratio of the intrinsic surface microscale, h, to the wind fetch, X.

$$\varepsilon = F(\xi, h/X) \tag{2}$$

where

$$\xi = C_0/U \tag{3}$$

U is the mean wind above the sea surface, C_0 is the phase velocity Of the dominant (spectral peak) waves. Parameter h has been introduced earlier [Glazman, 1986]. Its estimate for developed seas [Glazman and Weichman, 1989] is about 0.5 in. Under additional assumptions, detailed in section 8 of [(iii]?.rliar) and Srokosz, 1991], the dependence of ε on h/X can be foregone.: implying that h/X in (?) can be replaced by a constant (understood as the. average <h/X> representative of the global data Set) one is left with $\varepsilon \approx F(\xi)$. Since the actual wind fetch is usually unknown (and poorly defined), this simplification is of great practical value, Specifically, the SSB coefficient ε can be approximated by

$$\varepsilon \approx M\xi^{-m}, \tag{4}$$

where M and m are constants [Glazman and Srokosz, 1991], [Fu and Glazman, 1991]. Relationship (4) is highly useful because, under idealized sea conditions, ξ can be estimated give.n the mean wind and the significant wave height [Glazman et al. 1988] from altimeter measurements:

$$\xi \approx A(gH/U^2)^v \tag{5}$$

Parameters A and v have been determined theoretically [Glazman and Srokosz, 1991] as well as experimentally [Glazman and Pilorz, 1990]: $A \approx 3.21$, $v \approx 0.31$. When the sea conditions are more complicated than those required for a rigorous justification of (5), the latter should be viewed as an *ad hoc* function whose. relevance is to be tested by observations. Equation (5) then provide.s a measure of sea development which should be appropriately called the "pseudo wave. age" [Fu and Glazman, 1991]. Based on large amounts of data, this quantity has been shown to be practically useful, and radar return has been found to depend On ξ in a fashion consistent with the theoretical predictions [Glazman and Pilorz, 1990].

Aircraft and tower-hased radar experiments have suggested that, for a given radar frequency, ε can be sought as a function of U [Choy et al., 1984], [Walsh et al., 1984, 1991] or of U and $H_{1/3}$ [Melville et al., 1991]. The corresponding empirical relationships have been sought in the form:

$$\varepsilon = a_0 + a_1 U + a_2 H \quad (6)$$

Since. U is usuall y esti mated based on the radar cross section σ_0, an alternative form

$$\varepsilon = a_0 + a_1/\sigma_0^2 + a_2 H \quad (7)$$

has also been proposed [Melville et al., 1991]. Relationship (6) with $a_2 = 0$ is supported by actual sate.llitc data - as] eported by Ray and Koblinsky [1991]. Empirical coefficients a_n reported by different authors are summarized in Table 1.

Of course, equations (6) and (7) arc physically meaningless, unless parameters a_n can be interpreted in terms of appropriate dimensional quantities. It turns out that such a physically-based interpretation is possible, for example - by using (4) and (5). One can approximate (4) and (5) by

$$\varepsilon = F(U,H) \approx c_0 + c_1 U + c_2 H + c_3 UH + c_4 U^2 + c_5 H^2 + \ . \ . \ . \quad (8)$$

where dimensional coefficients c_n can be found from a Taylor series expansion of $F(\xi(U,H))$ about some (mean) values of U and H. Such an exercise would immediately demonstrate that: (i) equation (6) must include additional terms in order to parametrize the dependence of ε on sea conditions for a sufficientl y wide, range of sea states, and (ii) the coefficients of expansion, being functions of the. mean U and H, depend on the choice of these mean values. Therefore, when determined empirically, the. coefficients a_n in the GMFs (6) and (8) will differ among different investigators, unless such a determination is based on a global data set representing a statistically faithful sample of all possible sea slate.s.

3. Experimental procedure

The experimental appr each implemented in the present work is similar to that of [Born et al., 1982] and [Fu and Glazman, 1991]: we seek an optimal dependence of SSB on wind-wave characteristics by minimizing the total variance $<(\Delta\zeta)^2>$ of all sca level increments calculated for geographic points of interest. In contrast to the previous work, we shall use large sets of points uniformly cove.ring, an ocean area, i.e., sampled from many satellite passes. One parl of the total variance, denoted try $<(\Delta\eta)^2>$, which is due to SSB, is statistically dependent on wind-wave characteristics. Empirical values of M and m in (4) (or of a_n in (6)) are thus found by minimizing $<(\Delta\zeta)^2>$ as a function of these parameters.

Using 2.5 years' worth of Geosat altimeter observations, we assembled 20 global data subsets composed of 163 points each, providing uniform global coverage. The statistically significant optimal model parameters for global applications were obtained as averages over the 20 global subsets. To test the.sc.piirilrr)ctc.rsirnd to compare the global SSB model to the other models, we ultimately created three. independent subsets Of global data, each composed of Up to 400 points which had not been used in the derivation of the model parameters. For these three subsets we estimated $<(\Delta\eta)^2>^{1/2}$ for all algorithms under consideration.

The only quantitative measure of improvement of altimeter measurements which can be assessed based on satellite data alone is the mean squared decrement $<(\Delta\eta)^2>$ by which the. total sea level variance $<(\Delta\zeta)^2>$ is reduced owing to the SSB correction: the greater this decrement, the better the model performance. The square root of this quantity, called here the "accuracy gain," is reported in Table 1 for all algorithms tested including the optimized algorithms based on (6). It has been obtain as the average over the three test subsets.

A SSB model can be declared successful only if it reduces the total variance of sea level increments by an amount exceeding that resulting from the simplest standard model $SSB = a_0 \cdot H$. 'l'here.fore, we also estimated the optimal constant $\varepsilon = a_0$ for each data subset and the corresponding accuracy gain $<(\Delta\eta)^2>$, reported in Table 1.

4. Analysis of the results

1. Existing SSB mode.ls

Comparing the accuracy gains in the last column of Table 1, we find that the best performance among all existing SSB models is achieved by the wave-age-based model (4)-(5). All three algorithms A, B and C proposed by Melville et a]. - equations (6) and (7) with the coefficients listed in Table 1 - lead to an increase rather than a decrease in the total variance crfsurfiicc.height increments $<(\Delta\zeta)^2>$. The GMF proposed by Walsh et al. [1991] does improve the accuracy of sea level measurements in comparison to that without any SSB correction. However, the. improvement is marginal. A better result is achieved try the Ray-Koblinsky model, probably because the model parameters have been tuned based on global sate.llilc observations. However, the accuracy gain is still below that obtained with a constant ε.

The accuracy gain of 1.9 cm corresponding to $\varepsilon = a_0 = 0.018$ can be viewed as the benchmark to be surpassed by any practically useful algorithm. It is difficult at the present time to indicate the maximum accuracy again that would be achieved by the "perfect" algorithm, although it is clea r that the.2.5ciri achieved by two models - (4) and (6) - is not the limit to the improvement. The fact that the optimized model parameters, M= 0.026 and m=0.56, found in the present work for equation (4) have. not yielded an appreciable increase of the global accuracy (with respect to the accuracy gain obtained using the Fu and Glazman parameters) indicates that model (4) is robust and can be recommended for global applications.

2. Critique of polynomial models.

Comparing the three line.ar models base.d on (6) and analyzed in Table 1, one finds that even the most complete, three-parameter, version of (6) is less accurate than the two-parameter model (4). Remembering the comments made in section 2, this conclusion is not unexpected. Moreover, the experim ents reported in "1'able 1 confirm that expressions like (6) represent a crude approximation to a physically-b ased relationship (4). Indeed, the lwgalivc.values of a_2 appearing in 'J'able 1 can be obtained by expanding (4),(5) in powers of $(H-<H>)$. Onc might try to obtain a better approximation by including higher-order terms - as shown in (8). However, such an approach is unlikely to succeed: each additional term requires an additional empirical parameter whose determination represents a formidable problem. We believe that more progress can be achieved by using physically-based models which would more fully account for the. factors of sea sur-face's statistical geometry, for instance. the theoretical mode.1 (2) ill ustrated in Figure 8 of [Glazman irnd Srokosz, 1991].

5. Conclusions

Our analysis of regional SSB variations showed that the actual SSB variability is greater than what would be obtained based on **the** predictions of the. global GMFs. Respectively, the.rnaximutn accuracy gain of 2.55 cm reported in Table 1 is probably far below the actual, physically-based limit.

Further progress in SSB modeling can hardly be achieved by increasing the number of terms in polynomial GMFs. Theoretically justified models employing meaningful combinations of external parameters appear to be more promising. The pseudo wave age is one such combination. However, according to both the theory and the present data, this parameter amounts for only a part of the total SSB variability. As an additional relevant parameter, one may try to use the "generalized wind fetch" defined by (15). However, an additional e ffort is needed to establish its usefulness as a measure of the actual geometric fetch. Possibly, some additional information, for instance wind maps based cm satellite. scatterometry or/and characteristic lengths of dominant surface gravity wave.s available from SAR, might be of help.

Practical estimation of SSB based on satellite-supplied data has intrinsic limitations. In particular, wind sped and SWH do not necessarily provide a sufficient set of parameters from which 10 infer the actual geometrical properties of a random sea surface. responsible for SSB. The theory underlying the model (2)-(5) is highly idealized and may be inadequate in certain situations. The present analysis of regional SSB variations, as well as the above mentioned work by other authors, indicate that our understanding of physical mechanisms responsible for SSB is incomplete: we cannot point exactly at all possible causes of SSB variations.

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Table 1. Ratings of empirical model functions for SSB correction.

Model source and version	Type of experiment	Radar band, GHz	Wind-wave factors of c included in equation (#)	Empirical parameters in eqs (6), (7) and (4) a_0	a_1	a_2	Accuracy gain $<(\Delta h)^2>^{1/2}$ cm
M[91], (A)	Sea tower radar	" "	U, H; (6)	.0146	.00215	.00389	loss
" (B)			σ_0^{-2}, H; (7)	.0163	2.15	.00291	loss
" (C)			U; (6)	.0179	.0025		loss
W [91], (A)	Airborne radar	13.6	U; (6)	.011	.0014		1.24
" (B)		5, T--	U; (6)	.0074	.0025		N/A
W [84], (C)		36.0	U; (6)	-.0019	.0012		N/A
R&K [91]	Geosat altimeter	13.5	U; (6)	.0066	.0015		1.67
F&G [91]			ξ; (4)	.027	.88		2.54
			Optimized GMFs for global Geosat data:				
Constant c			none	0.018			1.94
Linear wind			U; (6)	.0056	.00091		2.25
Linear SWH			H; (6)	.0327		-.0022	2.01
Linear wind and SWH			U, H; (6)	.0245	.00122	-.0034	2.46
Present			ξ; (4)	.026	.56		2.55

Notation:
M[91]: Melville et al. [1991]; W[84] and [91]: Walsh et al. [1984] and [1991]; R&K [91]: Ray and Koblinsky [1991]; FG[91]: coefficients a_0 and a_1 are to be understood as M and **m** in eq. (4) for GMF of [Fu and Glazman, 1991]; "Linear wind": eq. (6) with $a_2 = 0$ and coefficients a_0 and a_1 optimized as described in section 5. "Linear SWH": eq. (6) with $a_1 = 0$, and a_0 and a_2 optimized as described in section 5. "Linear wind and SWH": eq(6) with all three coefficients optimized. "Present": eq. (4) with parameters M and **m** refined as described in section 5. Blank cells for the values of a_1 and a_2 signify that the corresponding terms are dropped in a given GMF.